Spatial variations in snow stability on uniform slopes : implications for extrapolation to surrounding terrain

by Christopher Cameron Landry

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences

Montana State University

Abstract:

Avalanche forecasters frequently perform field tests at study plots or other representative sites to reduce uncertainty regarding snowpack stability. This research investigated whether single snowpits represented stability throughout a carefully selected plot. The study utilized seven relatively uniform 900 m2 plots, three each in the Bridger and Madison Ranges of Southwest Montana, and one in the Columbia Mountains near Rogers Pass, British Columbia. Teams collected systematic samples from five snowpits, each containing ten 0.25 m2 stability-sampling cells, at each plot. Quantified loaded column stability tests measured strength in a single weak layer. Collection of in-situ slab shear stress data enabled the calculation of a stability ratio. Altogether, eleven stabilitysampling trials were performed during 2000/2001 and 2001/2002, testing several weak layer types exhibiting a wide range of strengths. Of the 54 valid snowpit results, 28 (51.9%) represented plot-wide stability, 16 did not, and the remaining 10 pits were empirically unrepresentative of their plot. Three of the eleven plots sampled contained full complements of five representative snowpits. As an additional component of this study, a GIS-based model extrapolated Bridger Range plot stability data onto avalanche starting zones, with poor results. The results of this study provide sufficient evidence of local spatial variation in snowpack stability within relatively uniform plots to reject the hypothesis that stability at a single snowpit will reliably represent a plot. However, these results do not suggest that information from snowpits is not important. Experienced forecasters interpret study plot stability data conservatively and are capable of utilizing “targeted sampling” and a variety of other data to effectively reduce uncertainty about slope stability.

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APPROVAL

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Christopher Cameron Landry

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date March 25, 2002

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ABSTRACT

Avalanche forecasters frequently perform field tests at study plots or other representative sites to reduce uncertainty regarding snowpack stability. This research investigated whether single snowpits represented stability throughout a carefully selected plot. The study utilized seven relatively uniform 900 m^2 plots, three each in the Bridger and Madison Ranges of Southwest Montana, and one in the Columbia Mountains near Rogers Pass, British Columbia. Teams collected systematic samples from five snowpits, each containing ten 0.25 m^2 stability-sampling cells, at each plot. Quantified loaded column stability tests measured strength in a single weak layer. Collection of in-situ slab shear stress data enabled the calculation of a stability ratio. Altogether, eleven stability-sampling trials were performed during 2000/2001 and 2001/2002, testing several weak layer types exhibiting a wide range of strengths. Of the 54 valid snowpit results, 28 (51.9%) represented plot-wide stability, 16 did not, and the remaining 10 pits were empirically unrepresentative of their plot. Three of the eleven plots sampled contained full complements of five representative snowpits. As an additional component of this study, a GIS-based model extrapolated Bridger Range plot stability data onto avalanche starting zones, with poor results. The results of this study provide sufficient evidence of local spatial variation in snowpack stability within relatively uniform plots to reject the hypothesis that stability at a single snowpit will reliably represent a plot. However, these results do not suggest that information from snowpits is not important. Experienced forecasters interpret study plot stability data conservatively and are capable of utilizing "targeted sampling" and a variety of other data to effectively reduce uncertainty about slope stability.

INTRODUCTION

Snow avalanches fall harmlessly by the hundreds of thousands throughout the uninhabited and unvisited mountains of the world each winter season (Armstrong and Williams, 1986). However, these otherwise harmless avalanches become potential hazards whenever and wherever people do enter the mountain realm (McClung and Schaerer, 1993), and lives and property are lost. Between 1970 and 1995, 365 people died in avalanche incidents in the United States (Logan and Atkins, 1996) and another 220 people were killed in Canada (Jamieson and Geldsetzer, 1996). Although those statistics reflect a wide variety of incidents, it has been persuasively argued that, "... a major source of [avalanche] fatalities and accidents is failure in human perception; people perceived the state of instability of the snow cover to be something other than it was" (McClung, 2000). This study evaluates the perceived value, and underlying reliability, of field measurements of snow cover instability performed by avalanche experts.

World-wide, public and private sector avalanche forecasters are employed to evaluate avalanche conditions and apprise recreationists, transportation corridor managers, local government public safety officials, and other mountain enterprise operators of current and future danger (Williams, 1998). Their work spans avalanche hazards ranging in spatial scale from a few avalanche paths encompassing one or two square kilometers to several mountain ranges consisting of thousands of square kilometers of terrain and hundreds of avalanche paths. Similarly, their "products" range in temporal specificity from "now" forecasts triggering specific operational responses, implemented within minutes or hours, to multi-day forecasts anticipating changing conditions and future risk mitigation actions.

McClung (2000) defined the practice of avalanche forecasting as, "… the prediction of current and future snow instability in space and time relative to a given triggering (deformation energy) level". It follows, then, that the goal of a forecaster is to "… minimize the uncertainty about instability introduced by the temporal and spatial variability of the snow cover, [by] incremental changes in snow and weather conditions, [and by] variations in human perception and estimation" (McClung, 2000). The process of preparing an avalanche forecast is sometimes supported by historic avalanche records retrieved by a computer program, or by the modeling of snowpack conditions across large areas, or by an "expert system" that combines both of those elements. However, even where those technologies are applied, so-called "conventional" avalanche forecasting remains the dominant forecasting methodology, an iterative and inductive mental exercise in the repeated collection and interpretation of data spanning a wide range of "informational entropy", or ease of interpretation and relevance (LaChapelle, 1980; McClung, 2000). The human capacity of skilled and experienced avalanche forecasters to grasp, appropriately weight, synthesize, and extrapolate such wide-ranging data has yet to be matched by computers (Schweizer and Föhn, 1996). Still, at least some uncertainty exists in every avalanche forecast.

Since avalanche forecasters seek to minimize uncertainty regarding instability, evidence of instability obtained from the observation of actual avalanches is customarily considered unambiguous, "low entropy", "scaled" information of the utmost relevance and, as such, given the highest weighting (LaChapelle, 1980). In the absence of actual avalanche observations, or to corroborate the evidence they present, field measurements of snowpack stability obtained from in-situ "stability tests" are also considered relevant, low entropy data. In-situ stability tests measure the critical "triggering" load, or deformation energy required, for snowpack rupture in a limited number of samples. However, it is rarely safe to conduct in-situ stability tests within avalanche starting zones, particularly when conditions approach the threshold of avalanching (CAA/NRCC and Schleiss, 1995; Föhn, 1987; Föhn, 1988). Further, it is infeasible to obtain stability test data from every starting zone of interest, given the magnitude of terrain that most forecasters evaluate (Armstrong, 1991). Finally, some starting zones may simply be inaccessible.

For these reasons, avalanche forecasters routinely perform stability tests at proxy "study plots" carefully selected to reveal conditions presumed to be "representative" of nearby avalanche terrain but without the hazards associated with entering that terrain (McClung and Schaerer, 1993; Fredston and Fesler, 1994). Consequently, unlike the more easily interpreted meaning of actual avalanche observations, study plot stability test data interpretation does contain informational ambiguity due to unknown spatial variations in snowpack characteristics between the study site and avalanche starting zones (Birkeland, 1997). Linking stability measured at the scale of sampling performed at a study plot to the relevant scales of prediction – single starting zones, an array of starting zones, or regions within a mountain range – requires extrapolation. Improved understanding of the reliability of stability test results, and of the spatial relationships between study plot stability and stability in adjoining and distant terrain, could significantly improve forecasters' perception of the meaning of stability test results and, thereby, reduce uncertainty.

As an avalanche forecaster working from 1990 through 1998 on a quarry access road near Marble, Colorado, I was confronted with the challenge of extrapolating snowpack stability information from study plots onto some eight square kilometers of "uncontrolled" and active avalanche terrain located inside the federally designated Raggeds Wilderness Area (Landry, 1994). In seven winter seasons over 700 natural avalanches (U.S. Class 2 size or larger) fell in the subject terrain and some 72 avalanches from 94 starting zones reached the quarry road (Landry, 1998), with only one minor incident. To evaluate the sensitivity of the snowpack to additional precipitation loading, traditional "collapse" stability tests (McClung and Schaerer, 1993) were utilized and the development of a quantified loaded column stability test was begun (Landry, 1998 and 1999). Two specific case studies during that period provide the impetus for the proposed research.

In the first instance, traditional collapse stability tests at a study plot adjoining the quarry road produced consistent shear fracturing results in a 40 cm slab under the equivalent of 37-50 mm of precipitation water equivalent of additional load. The next day, with a storm in progress, an adjoining avalanche path some 500 meters northwest of and 200 meters higher than the study plot produced a U.S. Class 3 size avalanche that hit and buried the road as the storm HNW reached 41-43 mm. Several adjoining paths also produced significant events within hours of the first event and within the range of 37-50 mm HNW of new loading, and all events appeared to have run in the same weak layer tested at the study plot.

A second case was documented involving the same study plot and adjoining avalanche path during the winter of 1998/99. Following a significant storm and avalanche cycle I conducted an analysis of the precipitation loading responsible for a deep slab avalanche to the road and cracking and collapse of the study plot snowpack. It revealed that the snowpack in both locations had failed under very similar levels of additional shear stress (aprox. 340 N/m^2). While no loaded column stability tests had been performed before the storm, the post-storm analysis suggested that the study plot snowpack and the avalanche path would have presented very similar pre-storm stability conditions. Several more adjoining starting zones had also produced U.S. Class 3-4 avalanches running in the same basal depth hoar weak layer.

Surprisingly little research has evaluated this widespread practice of extrapolation of stability/instability data from study plots to avalanche terrain. This is a matter of substantial interest to field practitioners who, in the absence of "better" (lower entropy) information, must often make significant assumptions based on study plot stability data. Avalanche researchers modeling snowpack characteristics and instability based on study plot meteorological data are also concerned with scaling the output of their modeling "up" to the sub-region or regional spatial scale. My experience while working in Colorado as a consulting avalanche forecaster suggests that correlations between study plot instability and instability in adjoining terrain sometimes *seem* to exist but at other times clearly do not, and those observations instigated this research.

RESEARCH HYPOTHESES

This study's objectives are to evaluate the reliability of snowpack stability test results obtained at carefully selected study plots and, then, to develop and evaluate a spatial model of avalanche starting zone stability which deterministically extrapolates measurements of Bridger Range study plot stability onto adjoining avalanche terrain. I investigated three hypotheses regarding study plot stability, at three spatial scales:

1. Stability measured at a randomly selected snowpit location within a carefully selected study plot will demonstrate a significant probability of predicting the mean stability of the entire study plot.
2. Stability measured at a study plot will reliably predict avalanche starting zone stability within 1-2 km of the study plot when adjusted for spatial variations in snowpack characteristics caused by elevation, aspect, slope angle, and redistribution of snow by wind.
3. Stability measured at a study plot will exhibit systematically decreasing correlation to stability in increasingly distant avalanche terrain and, therefore, will not predict stability throughout an avalanche region.

If stability testing at randomly selected sites within carefully selected study plots does not reliably indicate mean stability throughout a study plot (hypothesis #1), this will constitute an important finding regarding the measurement of stability at a very small spatial scale and compel avalanche forecasters to reconsider the weighting they give to study plot stability tests. Rejecting hypothesis #1 would also nullify hypotheses #2 and #3. If hypothesis #1 is not rejected, and snowpit stability tests reliably measure study plot stability, analysis of hypothesis #2 could reveal the absence of a significant relationship between stability at a study plot and stability in nearby terrain. This finding would nullify both hypotheses #2 and #3 and cause avalanche forecasters to seek other, more reliable sources of starting zone stability information. Conversely, strong region-wide correlation of stability measured at single or multiple study plots with starting zone stability would be a very important finding. Alternatively, it is possible that closely spaced study plots will present overlapping zones of high-confidence correlation between study plot stability and starting zone stability, but “gaps” of low-confidence correlation will be found between more widely spaced plots.

LITERATURE REVIEW

Several relevant themes are reviewed within the snow avalanche research literature. These include 1) avalanche forecasting principles and data collection, 2) snowpack stability testing and indices, 3) spatial variation of snowpack properties, 4) modeling snowpack stability and 5) modeling snowpack accumulation.

Avalanche Forecasting Principles and Data Collection

Most operational avalanche forecasting programs in the United States rely on "conventional" methods (Williams, 1998). Conventional avalanche forecasting is an iterative and inductive integration of at least three categories of contributory factor information. The objective of the iterative, inductive process is to minimize uncertainty by repeatedly seeking "low entropy", easily interpreted and relevant information (LaChapelle, 1980; McClung, 2000). Contributory factor information categories have been defined by McClung and Schaerer (1993) as Class III (meteorological), Class II (snowpack stratigraphy and state) and Class I (stability) information (listed in order from high- to low-entropy). Birkeland (1997) has proposed adding a fourth Class of data to the scheme, representing terrain. A synthesis of these data classes, and examples of the data they represent, is presented in Table 1.

Class I stability information includes the stability test data collected during this research. Such data have been considered especially important when forecasting slab avalanches originating in older layers within the snowpack (Armstrong and LaChapelle, 1976). McClung (1998) also describes the importance of objective Class I snowpack stability information during periods of "conditional stability", when conditions are not obvious and human perception of the spatial distribution of (in)stability, and the probability of directly measuring (in)stability, are poorest.

Table 1. Avalanche Forecasting "Contributory Factor" Data Classification.

Class	*Information*	*Examples of data*
I	Stability	Stability test results, avalanche observations, explosive testing ...
II	Snowpack	Weak layer type, slab thickness, slab density, snowpack height ...
III	Meteorological	New snow water equivalence, wind speed and direction, air temperature ...
IV	Terrain	Slope angle, elevation, aspect, slope curvature, vegetation, substrate ...

Although Class I stability data are vital to conventional forecasters, collecting the data is problematic. Identifying data collection sites that balance the need for reliable Class I snowpack stability information indicative of avalanche starting zone conditions against the risk and practicality of obtaining that information requires skill and experience (Föhn, 1988; CAA/NRCC and Schleiss, 1995). Also, some avalanche starting zones may simply be inaccessible, and as the geographic scale of the stability forecast area grows, it is increasingly difficult to obtain data at an ideal (low entropy) spatial resolution (Armstrong, 1991).

Consequently, forecasters identify safe and accessible study plots that seem likely to exhibit snowpack conditions representative of (at least) the adjoining avalanche terrain. There they collect stability data which are then integrated with other contributory factors and extrapolated, inductively, to the surrounding terrain using their understanding of snowpack processes and their forecasting experience to spatially modify the study plot results. Interestingly, individual forecasters may apply different weightings to the same set of contributory factor data to develop equally accurate forecasts, demonstrating that, "there is more than one way to forecast an avalanche" (LaChapelle, 1980). This study evaluates the underlying reliability of study plot stability measurements and analyzes the practice of spatially extrapolating stability test result data using a spatial modeling approach not previously described in the literature.

Snowpack Stability Testing and Indices

McClung and Schaerer (1993) described stability as "the ratio of the resistance to failure versus the forces acting toward a failure". While the avalanche forecasting literature initially concentrated on tensile stress/strength relationships (LaChapelle, 1966), shear fracture is now generally accepted as the primary mechanism in slab avalanche release (McClung, 1977; McClung and Schaerer, 1993). Consequently, researchers and field practitioners have developed a number of in-situ field tests measuring shear fracture strength.

The shear frame test produces a quantified, continuous measurement of shear strength. Researchers have refined the shear frame test procedure by evaluating the effects of frame size, load rates, and normal loads on tests results, and by developing stability indices based on shear strength measurements (Perla and Beck, 1983; Föhn, 1987b; Föhn, 1988; Jamieson, 1995). Shear frame tests are typically conducted at approximately level study sites (CAA/NRCC, 1995). Shear stress is introduced to a snow sample using a single rapid load parallel to and immediately above the suspect weak layer being tested. The shear frame procedure is more difficult to perform on a slope, does not necessarily identify the weakest layer in the snowpack, requires removal of the snowpack above the layer being measured, and is particularly difficult to perform when a relatively harder layer directly overlies the weak layer of interest. These shortcomings caused Perla and Beck (1983, p. 490) to advocate that, "the shear frame be replaced by a device that measures a more fundamental index of *gleitschict* [potential zone of shear fracture within the snowpack] strength".

The shear frame test quantifies shear strength in units of force but requires a certain degree of skill and painstaking preparation. Other stability tests have been developed which are less time intensive and more intuitively interpreted by recreationists. The Rutschblock test developed by the Swiss Army (Föhn, 1987a) yields an ordinal rating of the snowpack's vulnerability to skier-triggered shear fracture. In this test, shear stress is generated in an isolated column of snow with a surface area of 3 m^2 by the dynamic vertical load of a skier in a succession of increasing loads. Birkeland and Johnson (1999) introduced a "stuffblock" test that utilizes the same testing approach as the Rutschblock – successively increasing dynamic loading of an isolated column of snow – but at a smaller sample size of 0.09 m^2. Efforts to evaluate and calibrate the two tests with other tests have yielded significant correlations between the shear frame and Rutschblock (Föhn, 1987a; Jamieson and Johnston, 1992; Jamieson 1995) and the stuffblock and Rutschblock (Birkeland and Johnson, 1999). Backcountry recreationists and professional avalanche forecasters have adopted the Rutschblock and stuffblock tests as relatively simple, quick, and efficient techniques for testing current snowpack stability, given prudent and skilled interpretation.

Other field stability tests include the "compression" (tap) test (CAA/NRCC, 1995) and the "collapse" (loaded column) test (McClung and Schaerer, 1993). Jamieson and Johnston (1997) have evaluated the compression test and correlated its results with Rutschblock results and skier-triggered avalanching. Like the stuffblock, the compression test employs a successive series of dynamic loads upon a 0.09 m^2 isolated column of snow, and can be performed on sloping or level terrain. The collapse (loaded column) test also employs an isolated column of snow but, rather than using repeated dynamic loads, blocks of snow are gently added to the top of the column until the column fractures in shear or collapses. If desired, the water content of the added blocks of snow can be estimated.

The Rutschblock, stuffblock and compression tests all differ from the shear frame test in that they are typically conducted on slopes and the normal load produced by the snowpack above the weak layer being tested is left largely intact. However, unknown effects produced by cumulative compression of the snow during the test procedures, and their ordinal results, make the Rutschblock, stuffblock, and compression test difficult to interpret or verify in terms of quantities of precipitation loading or shear stress. The collapse test, on the other hand, can yield results in terms of quantities of precipitation loading and Schaerer (1991) called for additional development of the collapse (loaded column) test. This study employs a more rigorous "quantified loaded column test" (Landry et al., 2000) designed to produce continuous measurements of shear strength as well as express test results in terms of precipitation loading.

Stability indices have historically summarized shear frame test data by relating measured shear strength with shear stress introduced by the gravitational load of the in-situ snowpack above the tested weak layer (Föhn, 1987b and 1988). Other stability indices based on shear frame test results incorporate the effects of sample size and normal pressure, and account for human-trigger loads (Föhn, 1987b; Conway and Abrahamson, 1984; Jamieson, 1995). However, McClung and Schweizer (1999) cast doubt on the premises underlying stability indices (ratios) through an analysis of the mechanics of slab failure, size-effects related to stability tests, and the effects of slab properties on stability tests and skier-triggering. Further, none of the indices contain information about the spatial distribution of stability.

Spatial Variation of Snowpack Properties

Variation in stability on the scale of a particular, single slope has been investigated as a manifestation of so-called "deficit zones" (Föhn, 1988). Deficit zones, or "super-weak areas", are pre-requisites to natural avalanching (Bader and Salm, 1990; Schweizer, 1998). Conway and Abrahamson (1988) utilized shear strength measurements and a 'stationary random process' statistical technique to model stability variations on a single slope caused by hypothesized deficit zones. Jamieson (1992) measured distributions of Rutschblock test scores on single, uniform slopes, identifying the probability of a test falling within one 'degree' (one step in the rank order) of the slope's median score.

At the larger spatial scale of adjoining slopes, Bradley (1970) investigated the link between spatial and temporal patterns in "deep slab" avalanches. Dexter (1986) documented systematic variations in snowpack depth and strength due to variations in slope aspect and elevation over an area of 10 km^2. Substantial spatial variations between similar slopes in stability-related snowpack characteristics has been documented (Birkeland et al., 1995). Föhn (1988) suggests that many snowpack parameters vary to the same extent, including shear strength. Stability variation within avalanche starting zones is well known but does not easily lend itself to field measurement (Föhn, 1988).

Spatial variation research at the scale of many public-safety avalanche forecasting programs is limited. Such programs typically evaluate conditions over hundreds, even thousands of square kilometers (Williams, 1998). Jamieson and Johnston (1992, 1994) conducted extensive field trials in several ranges of British Columbia to develop a stability index for skier-triggered avalanching using the shear frame. The index was evaluated on a single slope scale and used to monitor the stabilization of a significant weak layer associated with numerous skier-triggered avalanches over areas within a 10-15 km radius of the study sites. While their index values were consistent with the gradual decline in skier/human triggered events in at least one region, triggered events did continue and were attributed to terrain- or weather-related "anomalies" in the snowpack.

They did not discuss or elaborate on any spatial patterns of avalanche activity or snowpack characteristics they observed during the study.

Birkeland (1997, 2001) advanced a geographic approach to stability research with his Bridger Range study in southwest Montana. The study deployed teams of field observers to 70 data collection sites spanning a distance of almost 40 kilometers. Data collected by the teams was analyzed to reveal linkages between stability and a set of variables measuring terrain, snowpack, and snow strength parameters. His thesis that the Bridger Range comprised a single "avalanche region" with similar avalanche conditions was generally supported by his findings that terrain parameters roughly determined stability patterns, rather than location within the Range. However, Birkeland did not correlate his findings with stability test results from study plots.

Modeling Snowpack Stability

Class III (meteorological) and Class II (snowpack stratigraphy and state) study plot data have been utilized by researchers pursuing a wide variety of statistical avalanche forecasting strategies at the regional and local scale (Good and Amman, 1994). Expert systems that model regional snowpack characteristics from point meteorological inputs (Giraud et al., 1994; Durand et al., 1999) or that combine meteorological, snowpack, geographic, topographic and field observations of avalanche activity (Bolognesi, 1988), are under continued development. Rink (1987) used discriminant and cluster analyses to identify key groups of geographical parameters (termed "geosystems") influencing avalanche formation including the definition of "slope climates" characterizing terrain at a local or regional scale. Buisson and Charlier (1989) developed an "expert system" combining a GIS digital terrain model composed from an irregular triangulated net with meteorological inputs and "specialist reasoning" to model stability and avalanche dynamics in a single path. The model required considerable avalanche experience to specify numerous boundary condition parameters. Chernouss and Federenko (1998) evaluated the spatial distribution of avalanche release probability at a local, single-slope scale, modeling slab characteristics and verifying the model with slab thickness measurements. However, Class I stability data have generally not been incorporated in these statistical methods or models, frequently citing the difficulty of estimating the spatial variation of snowpack stability and, hence, implying the difficulty in extrapolating stability measurements from study plots.

Process-oriented studies incorporating measured or modeled snowpack characteristics and processes from study plot (or point) data sources are of particular relevance to this thesis research. Judson et al. (1980) developed a deterministic, process-oriented approach to modeling snowpack stability at a local scale. They modeled snowpack processes for a "theoretical avalanche" designed to replicate the behavior of an array of 13 avalanche paths. The model proved effective in identifying artificially triggered avalanche days but poor at identifying non-avalanche days, perhaps because it employed no measured Class I stability test data due to problems with quantification.

In British Columbia, Canada, the Ministry of Highways presently employs a promising methodology at Kootenay Pass. It combines a "nearest neighbor" module (which matches current contributory factor conditions to an historic avalanche occurrence and weather database) with a rule-based computerized snow profile evaluation module (McClung, 1994). The nearest neighbor module requires forecasters to evaluate their "degree of belief" in the analysis before generating its final output. The snow profile evaluation module includes a "certainty factor" ranking the avalanche potential of individual snowpack elements according to forecaster-defined rules incorporating conventional data. Forecasters presently employ these two modules at a large local scale (within 10-15 km of the study plot) and their success "approaches human [conventional forecasting] capability in forecasting accuracy"(McClung, 1994, p. 424). Those results suggest that the inclusion of Class I stability information is critical for the success of process-oriented numeric forecasting systems.

Modeling Snowpack Accumulation

Investigations of mountain precipitation by snow hydrologists and others have described the influence of elevation and geographic location, relative to nearby terrain, on snow water equivalence (SWE) accumulation in mountainous terrain (Farnes, 1995; Sommerfeld and Smith, 1998; Balk et al., 1998). Complex interactions between terrain, air mass characteristics, microphysical processes in clouds, and atmospheric wind fields control the vertical distribution of precipitation in the mountains. In mid-latitude mountain ranges snow precipitation increases with elevation to a certain point (Barry, 1992). Further, Caine (1975) used snow course data from the San Juan Mountains of southwest Colorado to demonstrate that variation in distribution of SWE was also inversely related to elevation, meaning that high-elevation SWE is less variable than low elevation SWE.

Studies in and near the Bridger Range of southwest Montana confirm the relationship between precipitation and elevation. McPartland (1971) tracked snow precipitation for two winter seasons at 66 sites representing a variety of spatial attributes in the Bangtail Range located approximately 10 km east of the southern Bridger Range. After evaluating a number of spatial variables, including wind exposure, he concluded that elevation was the parameter that best predicted snowpack depth. Birkeland's (1997) study of elevation and aspect influences on snowpack conditions and stability in the Bridger Range found that snow depth generally increased with elevation, although slope aspect complicated the relationship. Birkeland (personal communication, 2000) considers elevation and easting (distance downwind from barrier) to be spatially autocorrelated in the Bridger Range and, in effect, a single variable (partially) determining SWE at a given location. Pipp and Locke (1998, page 34) also found, using a set of three snow/elevation and easting gradient transects at sub-alpine sites in the Ross Pass area of the Bridger Range, that both elevation and easting were "equally competent, linear predictors of snowfall [SWE]". Their linear function for the influence of elevation on SWE at all fifteen sampling points in their study area is:

$$\begin{gathered} SWE(mm) = -887 + 628\left[Elev(km)\right] \\ r^2 = 0.62,\ \mathrm{p} < 0.001 \end{gathered} \quad (1)$$

Snow hydrologists, charged with predicting snowmelt runoff from mountain watersheds, are interested in modeling SWE, and predicting snow-melt runoff, at spatial scales ranging from a single mountain basin to an entire mountain range. A network of instrument arrays operating throughout the western United States by the National Resource Conservation Service (NRCS), called SnoTel, measures snow precipitation and other weather parameters at wind-sheltered sites below treeline. Often, pairs of high/low-elevation SnoTel sites are used to measure elevation differences in precipitation within a basin. Water management agencies, including NRCS, have developed numerous algorithms which are reasonably successful in modeling snowpack distribution below treeline from this network of SnoTel point data.

Modeling snowpack distribution (and SWE) in alpine terrain above treeline, however, has been found to be particularly problematic due to the redistribution of snow by wind. At the basin scale, Ingersoll (1996) empirically evaluated SWE in the Andrews Creek basin of the Front Range in Colorado, but the processes controlling distribution were not modeled. Winstral and Elder (1998) adapted a "fetch" algorithm originally developed for predicting snow drift in the Canadian prairies incorporating curvature and wind-exposure indices derived from a 30 m digital elevation model (re-sampled at 400m for deriving curvature). They found their empirical method was roughly twice as effective in explaining snowpack distribution at the 406 points measured above treeline as using a combination of elevation, radiation, and slope parameters. The single-basin scale of this and other SWE modeling efforts offers insights into snowpack distribution processes to avalanche scientists modeling stability in individual avalanche starting zones within basins.

Building on the numerous investigations during the 1970's and 80's of the physical laws governing snow drift conducted by Schmidt, Tabler, and others, increasingly complex physical models of snow drift in alpine terrain are emerging. Among the more recent, three-dimensional models is the work by Liston and Sturm (1998), in which a numerical snow transport model for complex terrain was developed. SnowTran-3D was tested during the 1997/98 winter by Greene et al. (1999) on an alpine ridge near Cameron Pass, Colorado. This limited trial produced an adequate simulation of the actual drifting at the site. Additionally, Gauer (1999) modeled snow scouring and deposition on the Gaudergrat ridge near Davos, Switzerland, using a physically based numerical method with a spatial resolution of 5 m^2.

Preceding these three-dimensional models are the earlier works by Föhn (1980) and Föhn and Meister (1983), that describe two-dimensional physical models of wind drift over mountain ridges. In the first of those studies, Föhn (1980) evaluated the snow mass flux produced by "wind power" from windward to leeward slopes of an alpine ridge. Fohn's (1980) empirically derived equation for the increase in snow depth produced by wind-power induced drift is:

$$H_{NS} = k\bar{u}^3 \left\{ {}^{m}\!/_{d} \right\} \qquad (2)$$

where H_{NS} represents the increase in snowpack depth, in meters per day, u is the 24-hour mean wind speed (meters/second), and k is an empirically derived coefficient $k = 8 \times 10^{-5} s^3 d^{-1} m^{-2}$.

This model was further refined (Föhn and Meister, 1983) by describing three general patterns of snow drift, related to ridge crest apex angles: 1) the formation of a snow cornice at the ridge crest, with an area of scouring just below the cornice (on the leeward slope), and a secondary area of enhanced deposition some distance further down the lee slope, grading into the 'normal' snowpack for that elevation, 2) enhanced deposition, without a cornice, immediately leeward of and attached to the crest, grading into the normal snowpack, and 3) scouring in the immediate lee of the ridge crest, with enhanced deposition down-slope and detached from the crest, grading into the normal snowpack. Föhn and Meister explain these patterns of drift using the combined effects of "plume" and "potential flow" models. The potential flow model was applied to precipitating snow while the plume model was applied to the erosion of a snowpack lying on the windward slope; both models assumed a wind flow perpendicular to an elongated ridge [such as occurs at the Bridger Range] and incorporate wind speed and terrain ("hump") shape. Föhn and Meister acknowledge that, in more severe terrain, the exact positioning of deposition elements, such as a cornice, may not be accurately estimated by the models.

STUDY AREA

The Bridger Range of southwest Montana, from Baldy Mountain to Flathead Pass (Figure 1), was chosen as the primary study area for this research because:

1) the topography of the Bridger Range is relatively consistent, with a single, generally north-south ridge axis and a long array of generally east-facing terrain, facilitating the identification of numerous potential study plot sites with similar characteristics,
2) steep, generally east-facing slopes, sparse vegetation near the ridgeline, and frequent precipitation events, with intervening periods of weather conducive to the formation of weaknesses within the snowpack, combine to create active avalanche terrain,
3) safe access to the potential study plot sites is possible
4) Bridger Bowl ski area and other researchers are collecting high quality meteorological data at a central location within the study area.

The Bridger Range lies within the Intermountain avalanche region of the United States (Armstrong and Armstrong, 1988; Mock and Birkeland, 2000). The snow climate of this area is also described as "transitional" (McClung and Schaerer, 1993) wherein characteristics of both continental and maritime snowpacks and weather are found. Winter weather in the Bridgers consists of low temperatures, long duration and strong wind events, and varying amounts of precipitation. Year-to-year snowpack depths in the

Figure 1: Bridger Range Study Area Map